AD 738853

SWERR-TR-72-1

FATIGUE PROPERTIES OF GUN BARREL MATERIALS

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TECHNICAL REPORT

Dr. Kailasam R. Iyer
and
Richard B. Miclot

January 1972

RESEARCH DIRECTORATE

WEAPONS LABORATORY AT ROCK ISLAND

RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
U. S. Army Weapons Command Research, Dev. and Eng. Directorate Rock Island, Illinois 61201	Unclassified
	2b. GROUP

3. REPORT TITLE

FATIGUE PROPERTIES OF GUN BARREL MATERIALS (U)

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

K. R. Iyer and R. B. Miclot

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1972	32	8

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. DA 1T061102B32A	SWERR-TR-72-1
c. AMS Code 501B.11.85500.02	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release, distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Weapons Command

13. ABSTRACT

A continuing program to determine the fatigue characteristics of gun barrel materials was initiated by the Research Directorate, Weapons Laboratory at Rock Island. The results of this program will lead to the prediction of fatigue damage in gun barrels and will facilitate the development of improved barrel materials. The outside surface temperatures of an M60, 7.62mm, gun barrel were measured during test firing at various locations along the length of the barrel. The temperatures across transverse sections of the barrel were calculated by the implicit finite-difference method. These data will be used to generate the stress-time-temperature profiles representative of service conditions of the barrel. Room temperature fatigue properties of Cr-Mo-V steel under axial push-pull and rotating-bending loading conditions were determined. The data were analyzed to study the effect of prestress on the fatigue properties of the material and to develop stress-life curves for design purposes. Detailed metallographic examination of the fatigue fractures was performed. The analysis shows that the effect of static tensile stress is to lower the amplitude of the alternating stress corresponding to the endurance limit of Cr-Mo-V steel and that the fatigue fracture characteristics of Cr-Mo-V are similar to those of fine-grained, quenched, and tempered steels. (U) (Iyer, K. R. and Miclot, R. B.)

DD FORM 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Cr-Mo-V Steel						
2. Fatigue						
3. Temperature Measurement						

AD

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steels.

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ACKNOWLEDGMENT

INTRODUCTION

Erosion of gun barrels refers to the progressive deterioration and enlargement of the bore. High temperatures (caused by the burning of the propellant), stresses (due to pressure, thermal gradients, and the swaging action of the projectile), abrasive and ablative wear, and the chemical reactivity of the combustion products contribute to the erosion phenomenon in gun tubes. Metallurgical examination of test-fired gun barrels has revealed that severe cracking, both tangential and radial, occurs in the bore near the breech end of the barrel. Cracks that interconnect cause material removal, whereas those that progress radially cause catastrophic failure.[1] Thus, crack nucleation and propagation, under repetitive-thermomechanical stresses in a reactive atmosphere, cause extensive damage in a gun barrel. An understanding of the phenomenon of fatigue under controlled environmental conditions will lead to better design parameters and will facilitate development of improved gun barrel materials.

A continuing program with the object of conducting a fundamental investigation of the fatigue behavior of rapid-fire gun barrel materials was initiated by the Research Directorate, Weapons Laboratory at Rock Island. Studies will involve the conventional gun barrel material (Cr-Mo-V steel) and will encompass materials that are considered potentially superior. Materials will be subjected to the repetitive application of stresses at temperatures simulating the conditions relevant to gun barrel application. Characteristics of nucleation and propagation of cracks, type and extent of plastic deformation, and critical crack sizes will be determined by metallographic examination.

For the accomplishment of this objective, an assessment of the magnitude and direction of the stresses operating on the barrel material and the relevant temperatures is necessary. Also, in the case of the current barrel material, information about fatigue of this material under simple conditions of stressing had not been obtained. Therefore, the efforts of the first year concerned primarily two definite areas: (1) determination of room temperature fatigue properties of Cr-Mo-V steel and (2) temperature measurements and calculation of thermal stresses, which form an integral part of the stress-time profile.

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EXPERIMENTAL

Fatigue Testing of Cr-Mo-V Steel

Fatigue tests were conducted at room temperature on heat-treated Cr-Mo-V steel under rotating-bending and axial loading conditions. The maximum stress-fatigue life (S-N) curves were determined for various values of minimum-to-maximum stress ratio, R. Fatigue tests at R=0.2, 0, -0.2, and -0.4 were performed on a Sonntag machine in which an alternating stress (σ_a) is superimposed on a static stress (σ_s).

The composition, heat treatment, and tensile properties at room temperature of Cr-Mo-V steel are given in Table I. The test specimens were machined from heat-treated gun barrel stock in such a manner that the longitudinal axis of the specimen was parallel to that of the stock. These specimens were then electropolished to remove the work-hardened layer and to provide a reproducible surface finish. The geometry and dimensions of the test specimen for fatigue under axial load are shown in Figure 1. Fatigue testing under conditions of R=-1 was carried out in an R. R. Moore machine.

The experimental setup and the instrumentation for fatigue testing are shown in Figure 2. A strain gage was welded to the loading springs of the Sonntag machine to monitor the loading conditions in the specimen during testing. After testing, the specimens were metallographically examined to characterize the fracture surfaces.

Temperature Measurements

Temperature measurements were made on the outside surface of Special M60, 7.62mm, rapid-fire gun barrels (one-piece construction) during test firing under different schedules. The barrels were made of Cr-Mo-V steel and were in the unplated condition. Chromel-Alumel thermocouples were welded to the surface at various locations along the length of the barrel and the emf's (which were later converted to temperatures) were measured by a high-speed recorder. From these values, the temperatures at various radial locations were calculated by the implicit finite-difference method.

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TABLE I

COMPOSITION, HEAT TREATMENT, AND TENSILE PROPERTIES OF Cr-Mo-V STEEL

a. Composition in weight percentages

C	Mn	Cr	Mo	V	Si	S	P
0.41	0.88	1.19	0.64	0.22	0.27	0.014	0.013

b. Heat treatment

Normalized at 1700°F for 2-1/2 hours, air-cooled
Hardened at 1575°F for 2-1/2 hours, oil-quenched
Tempered at 1210°F for 2-1/2 hours, air-cooled
Stress Rel. at 1100°F for 2-1/2 hours, air-cooled

c. Tensile properties at room temperature

Y. S. (0.2% offset)	-	145 ksi
T. S.	-	155 ksi
Elongation	-	17.6%
R. A.	-	57.8%

4.0"

1.5"

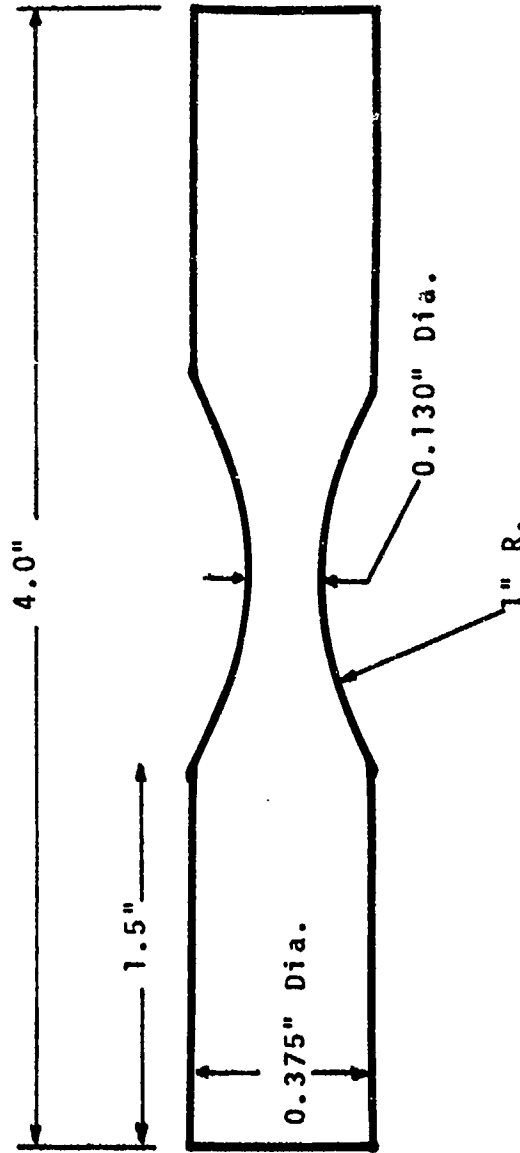0.375" Dia.

0.130" Dia.

¾" R.

FIGURE 1   Sketch of Fatigue Specimen, Push-Pull Type,
Employed in Sonntag Universal Fatigue Testing Machine
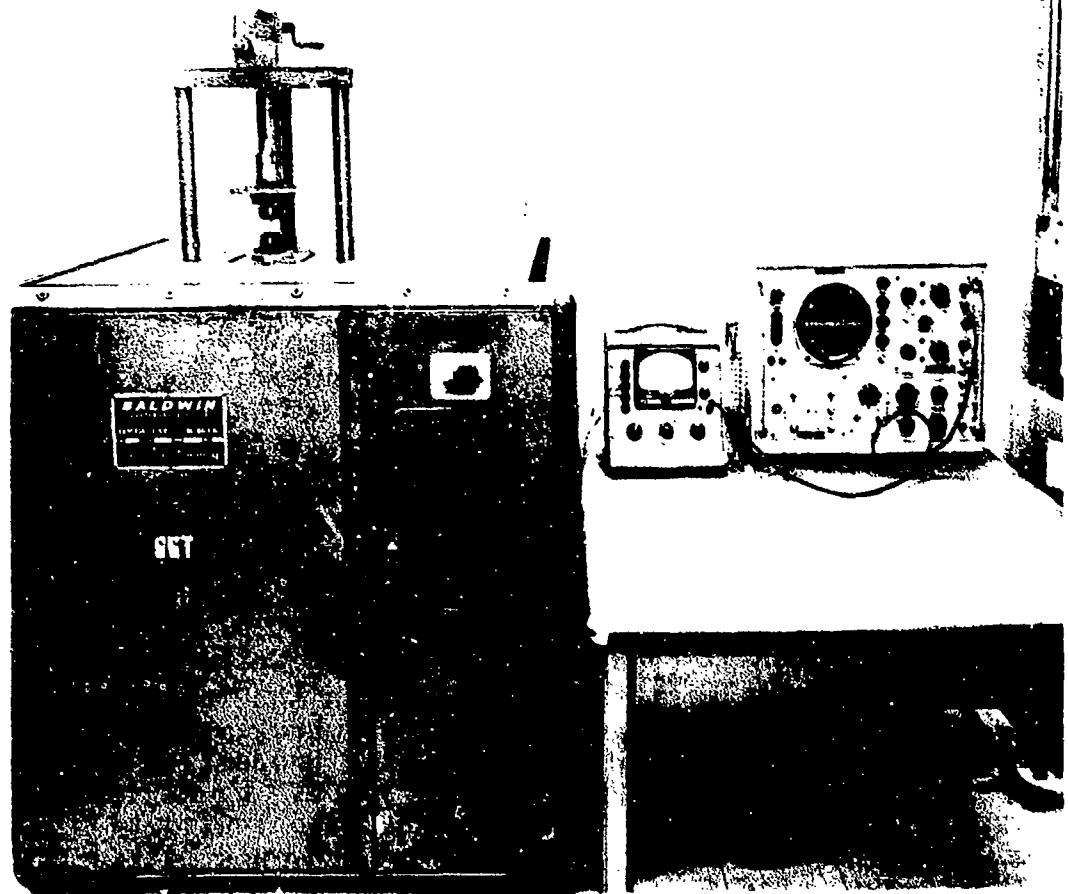
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FIGURE 2   Experimental Setup for
      Fatigue Testing under Axial Push-Pull Type Loading

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RESULTS AND DISCUSSION

Fatigue Tests

The results of the fatigue tests are presented in the form of S-N curves in Figure 3 for the various values of R. The curve for R = -1.0 is presented in the same diagram. The effect of the values of R and the static stress (σ_s) on the stress amplitudes (σ_a) corresponding to the endurance limit ($10^7 \sim$) of Cr-Mo-V steel is shown in Table II. Again, the data point for R = -1.0 is included. Direct comparison of fatigue data under axial and rotating-bending loading conditions should not be made. When the specimen is tested under axial loading, the entire cross section is subjected to the maximum stress, whereas only a small volume of material on the periphery of the specimen is subjected to maximum stress in a fatigue test conducted under rotating-bending type of loading. This fact illustrates why fatigue strengths are usually lower in axial push-pull loading than in rotating-bending.

For design use, data reported in S-N curves are customarily represented in the form of a Goodman diagram. A modified Goodman diagram which represents constant life cycles under various R values for Cr-Mo-V steel is presented in Figure 4. Before a Goodman diagram can be used for actual service cases, corrections must be made for such factors as geometry, size, surface conditions, stress states, and notches.

Theoretical predictions of fatigue life of materials are usually made, especially when design on the basis of fatigue is warranted and when fatigue data are lacking. A popular approach is to rely on the tensile properties of the material. The method of universal slopes[3] by Manson is based on this approach. The fact that the test data correlate quite well with predictions by Manson's method is of interest. The details of calculation are given in References 3 and 4. The experimental points for fatigue tests under rotating-bending conditions (R = -1.0) are shown in Figure 5. The agreement is considered good. The "universal slopes" in this method have a range of values: -0.4 to -0.8 for the plastic component and -0.08 to -0.16 for the elastic component. Values of -0.55 for the plastic component and -0.10 for the elastic component fit the experimental data for Cr-Mo-V steel.
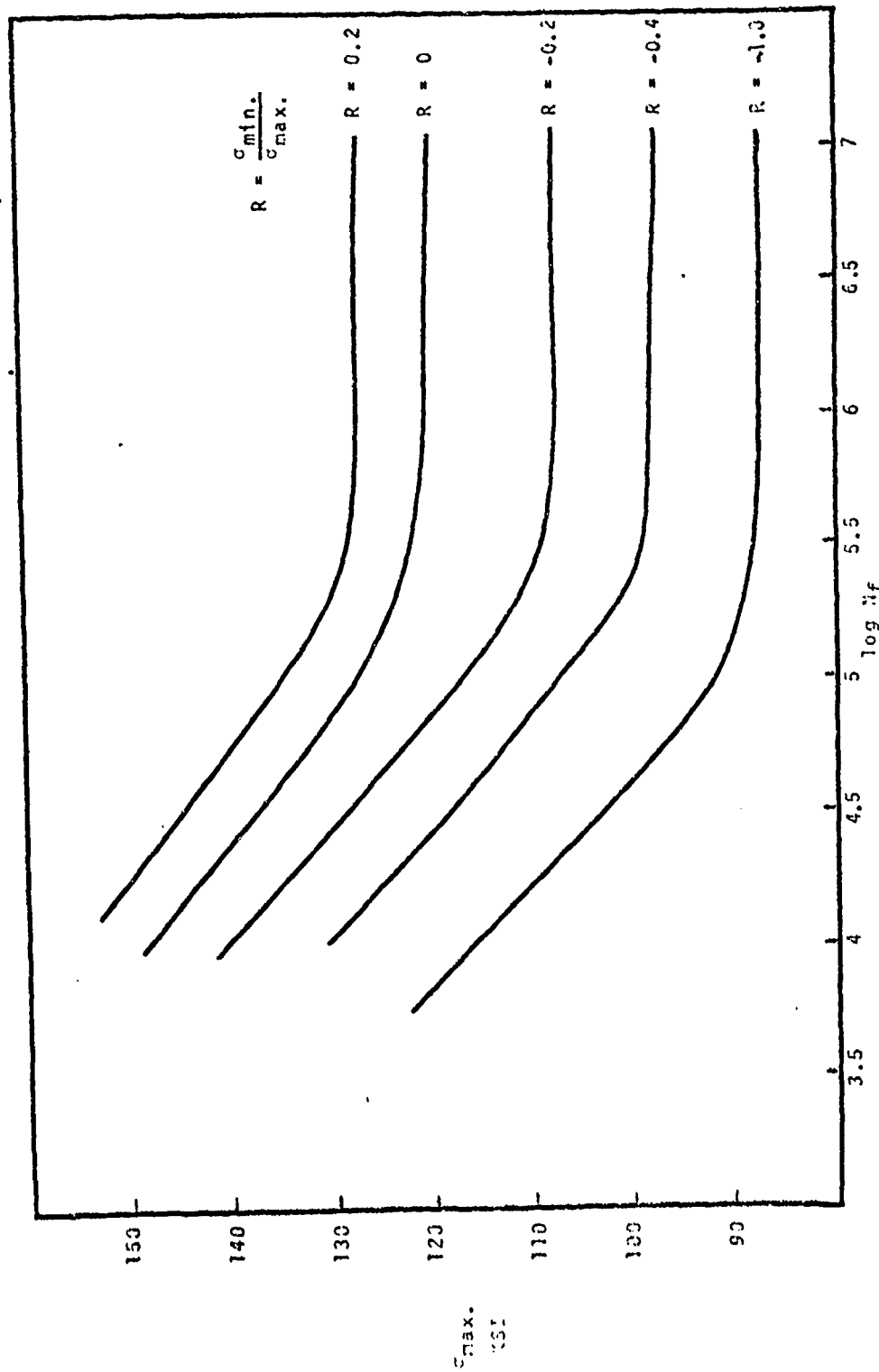
6

FIGURE 3   Peak Stress-Log Cycles Fatigue Curves for Cr-Mo-V Wrought Steel
Hardened and Tempered to 32-34 R_C, 145 ksi Yield Strength,
and 155 ksi Tensile Strength. Curve R = -1.0 Represents
Data from Rotating-Bending Tests

TABLE II

THE EFFECT OF THE VALUES OF R AND STATIC
TENSILE STRESS ON THE AMPLITUDE OF
ALTERNATING STRESS FOR AN
ENDURANCE LIMIT OF 10^7 CYCLES

R	σ_{max}	σ_{min}	σ_s	$\sigma_a = (\frac{\sigma_{max} - \sigma_{min}}{2})$
0.2	128	25.6	76.8	51.2
0	121	0	60.5	60.5
-0.2	108	-21.6	43.2	64.8
-0.4	98	-39.2	29.4	68.6
- -
-1.0*	88	-88.0	0	88

*Tests for R = -1.0 were conducted in an R. R. Moore machine.
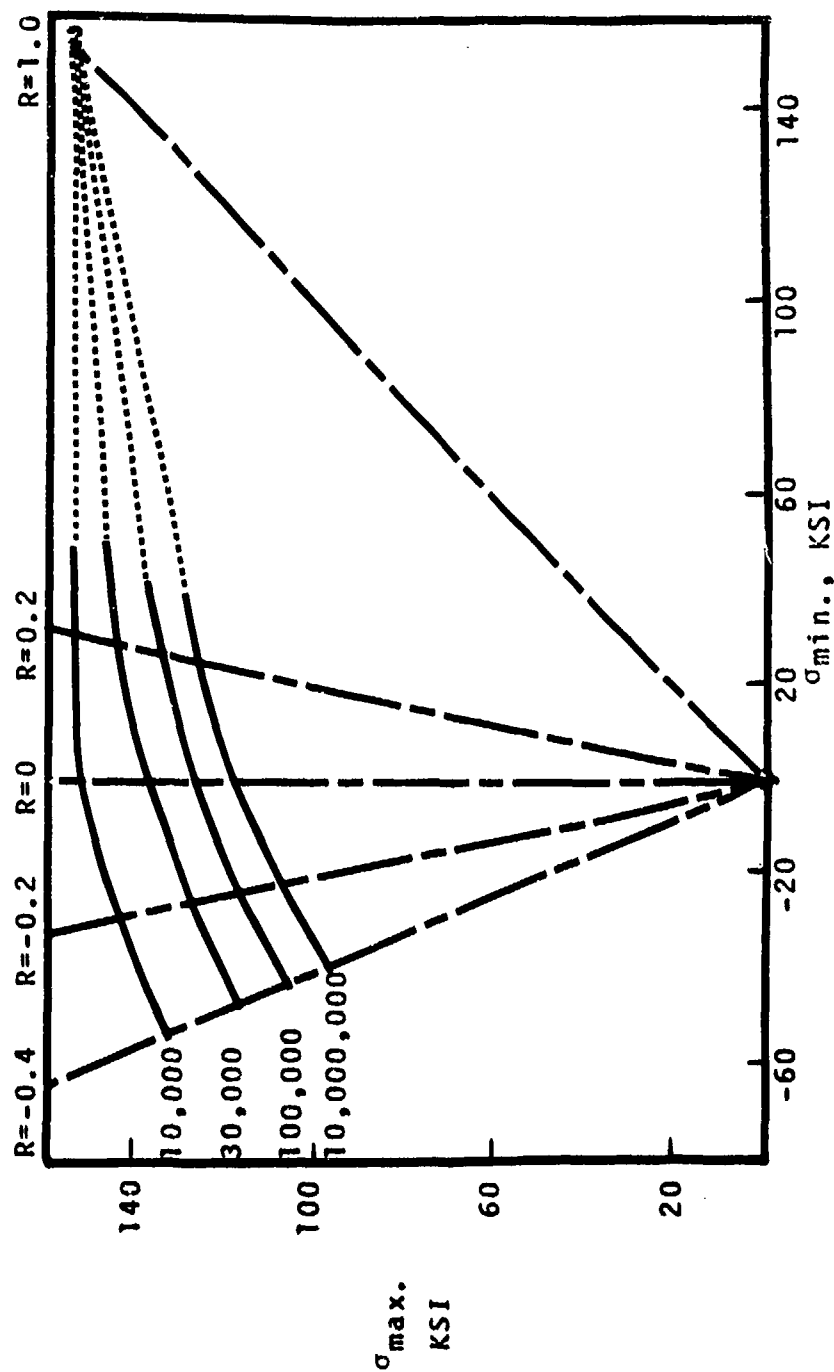
All stresses are in ksi units.

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FIGURE 4   Modified Goodman Diagram of Fatigue Test Data for Cr-Mo-V Wrought Steel Hardened and Tempered to 155 ksi Tensile Strength. Curves Represent Constant Life Cycles with Variation in Stress, σ, and Stress Rate, R.
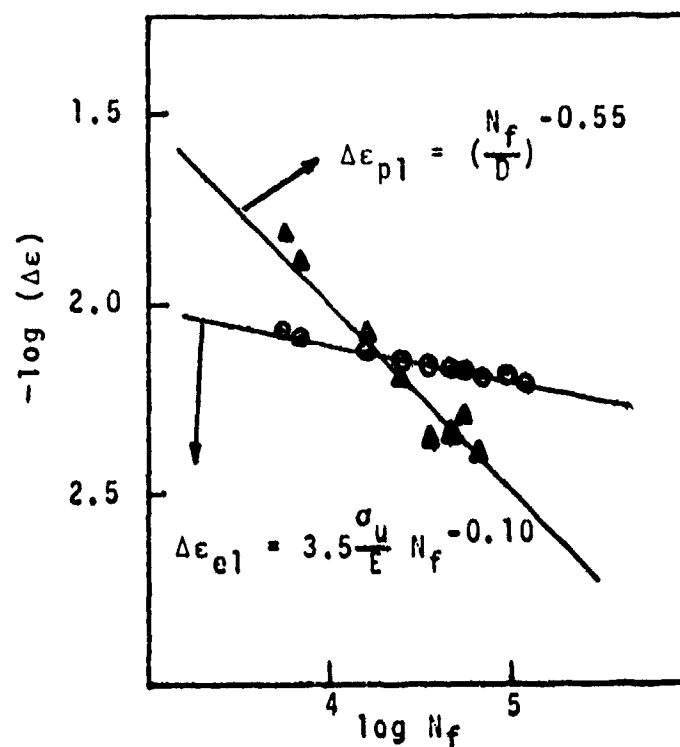
FIGURE 5   Dependence of Fatigue Life
of Cr-Mo-V Steel on Strain Amplitude

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Metallographic Examination of Fatigue Fractures

Before the fracture behavior of the gun barrel steel can be explained, the characteristics of the material must be described so that the observations and the analysis can be placed in proper perspective. The gun steel is usually normalized, quenched, and tempered to achieve a very fine grain size and a high toughness.[5] The toughness in the longitudinal direction of the bar stock is about three times the toughness in the transverse direction. The specimens were machined from the bar stock in such a manner that the length of the specimen was parallel to the longitudinal direction of the bar stock. The crack propagated in the transverse plane with reference to the gun barrel stock.

In the case of axial push-pull tests, the fracture surfaces were invariably damaged since, at the end of the test, the fracture surfaces were impacted against each other.

Macrographic examination of the fatigue fractures under rotating-bending condition revealed the following general characteristics. In all cases, fatigue fracture began near the surface and propagated through a major area of the cross section. The final phase of the failure was a ductile fracture followed by shear rupture. The crack propagation region was divided into a shiny region and a dull region. The shiny region is the result of crack closure during the compressive half of the cycle and possible rubbing. A typical fractograph of the fatigue fracture is shown in Figure 6b. The particular specimen was tested at a peak stress of 95 ksi. The fracture started from both sides, continued inward over an area of about 75 per cent of the cross section by fatigue, and caused failure by shear rupture. Comparisons can be made with fractographs (Figures 6a and 6c) of specimens which were tested at 105 ksi and 90 ksi, respectively. At high stresses, the fracture starts along three-fourths of the periphery, continues radially, and causes final failure by rupture. At low stresses, the fracture starts on one side, propagates over approximately 85 per cent of the cross section by fatigue, and ends as a ductile fracture.

Detailed metallographic examination of the fatigue specimens tested under rotating-bending conditions was carried out with a scanning electron microscope. In the crack propagation region, "ductile" regions (in which striations could be discerned) and "brittle" transgranular
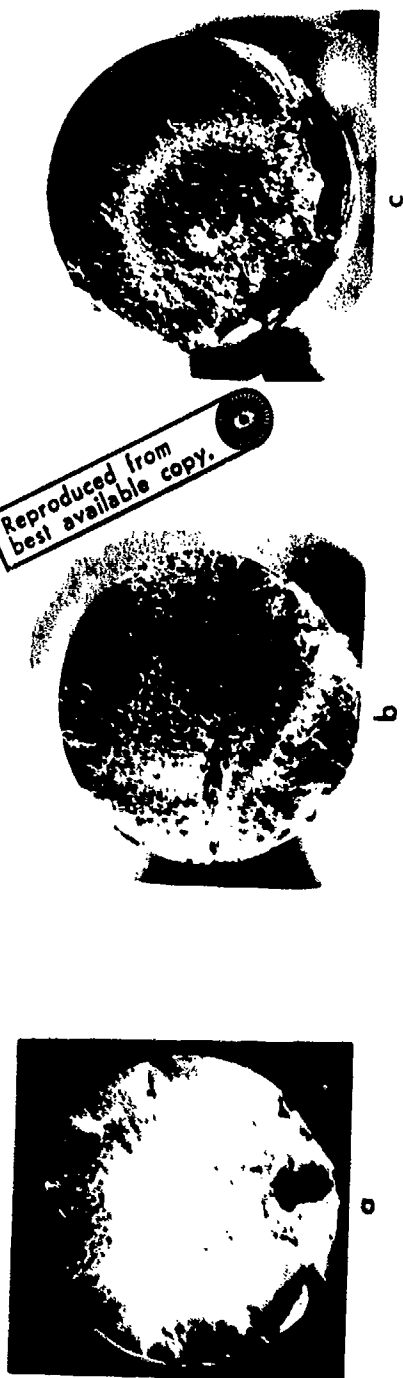
FIGURE 6   Macrographs of Fatigue Fractures of Specimens Tested
under Rotating Bending Type Loading

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regions were present. The relative area of ductile striated region decreases as the crack propagates. The interstriation distance remains the same or decreases slightly as the crack advances. This behavior is to be expected since, in rotating-bending fatigue tests, the stress is not uniform across the section, but decreases radially toward the center. The tendency of the striated region to change planes, as the crack propagates, causes microscopic tear. Some of these features can be seen in Figures 7 and 8 which are stereoscopic pairs of the crack propagation regions in two specimens. In some striated regions, orthogonal to the striations, a "hill and valley" type of structure can be seen. Such a feature has been observed in the ferritic regions of fatigue fractures of steels.[6] The final fracture region of a typical fatigue failure of Cr-Mo-V steel is shown in Figure 9. A mixture of small and large dimples are found in the ductile fracture region. The final shear rupture is characterized by small dimples.

In all respects, the general fatigue characteristics of Cr-Mo-V steel at room temperature are similar to those of quenched and tempered fine grained low alloy steels.[7,8]

Temperature Measurements

Various attempts were made to determine the bore surface as well as the outside surface temperatures of different gun barrels during this program. The details and the analyses of these tests will be published separately, later A few of these results, pertinent to the M60 barrel, will be presented in this report.

The recorded temperatures of the outside surface of the Cr-Mo-V steel, one-piece barrel at the various locations indicated on the curves, are shown in Figure 10. The firing schedule required six continuous bursts of 125 rounds with an intermediate cooling for 10 seconds. Bore surface temperatures were calculated by the implicit finite-difference method based on the measured outside surface temperature values. The bore surface and the outside surface temperatures as a function of time for the region 3 75 inches from the breech end (1.75 inches from the origin of rifling), are shown in Figure 11.
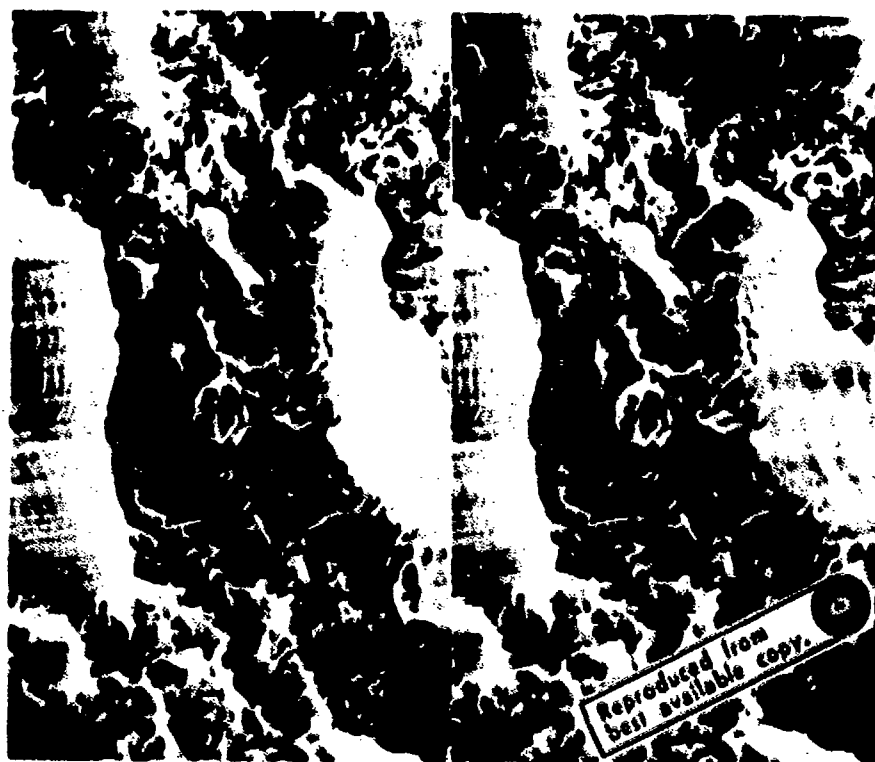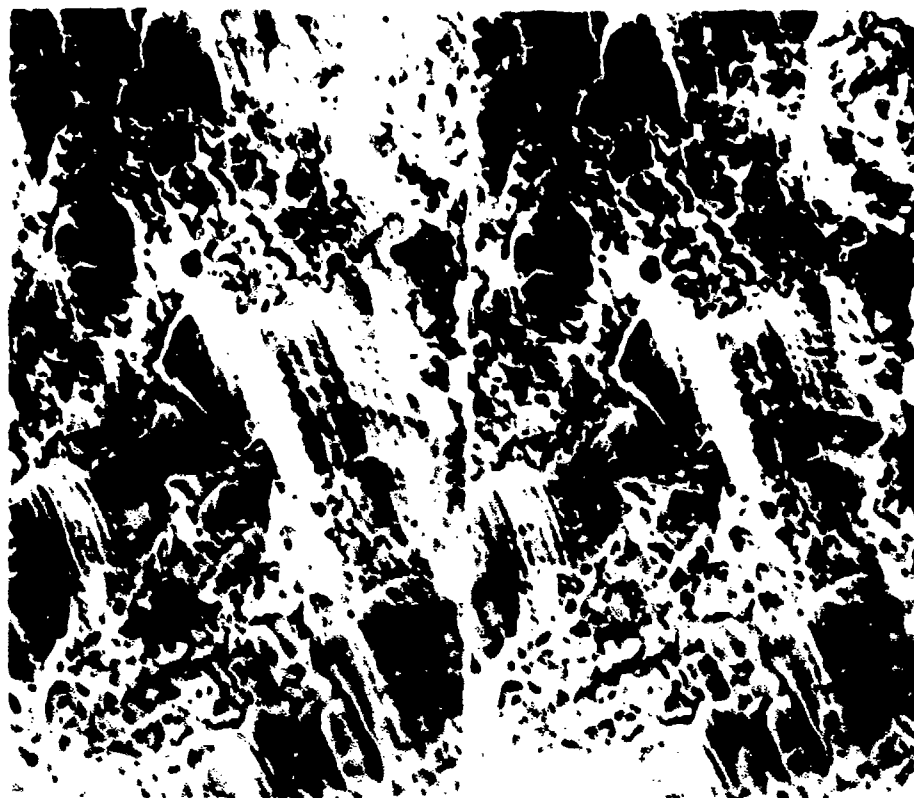
13

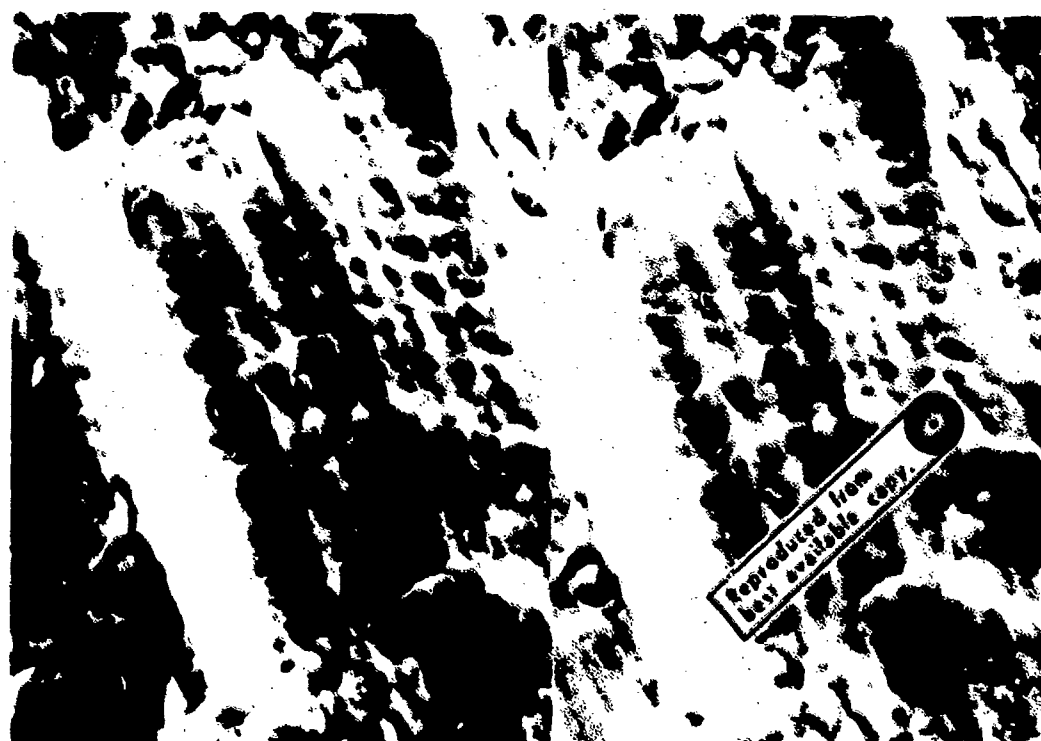FIGURE 7   Scanning Micrograph
            (Stereoscopic Pair) of Fatigue Crack
        Propagation Region in Cr-Mo-V Steel.   1000X.

14

1000X

3000X

FIGURE 8   Scanning Micrograph
(Stereoscopic Pair) of Fatigue Crack
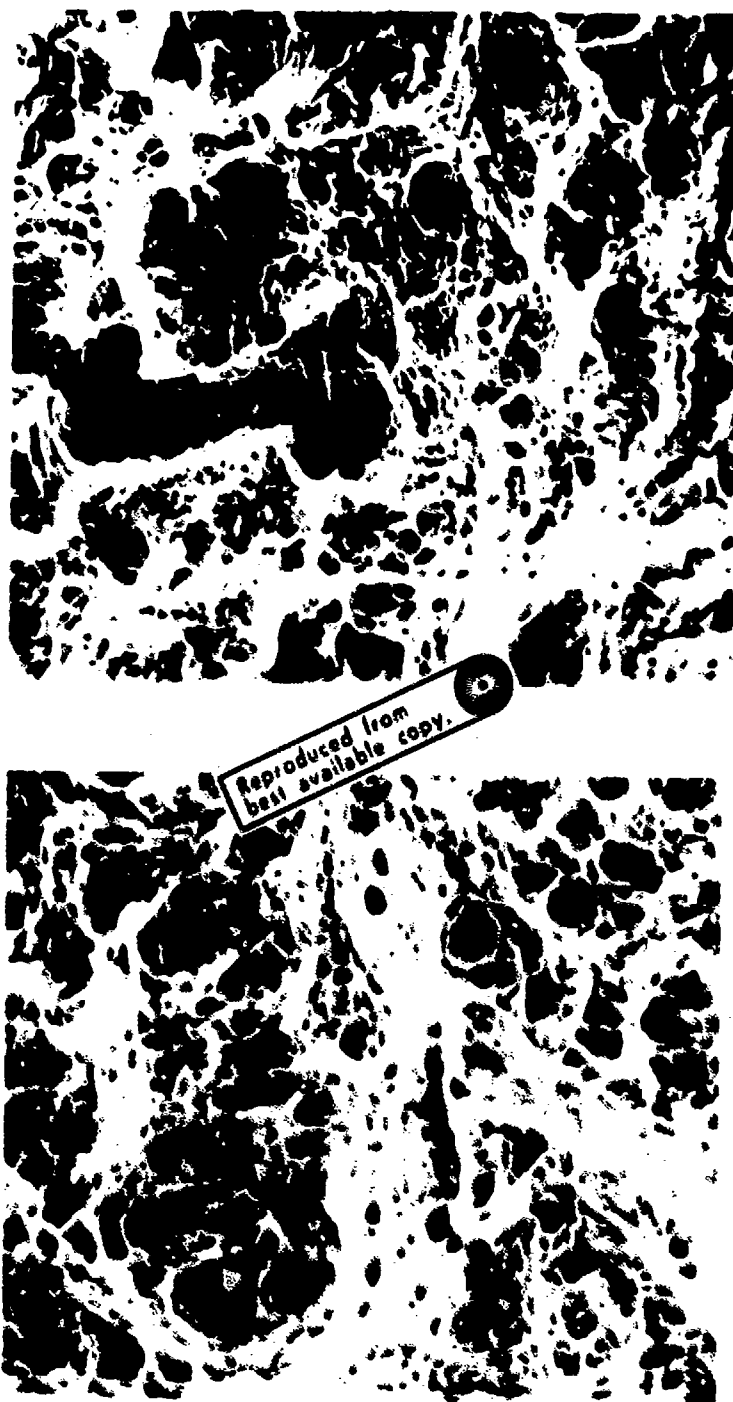Propagation Region in Cr-Mo-V Steel

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FIGURE 9   Scanning Micrographs of the
Final Fracture Region of Fatigue Failure
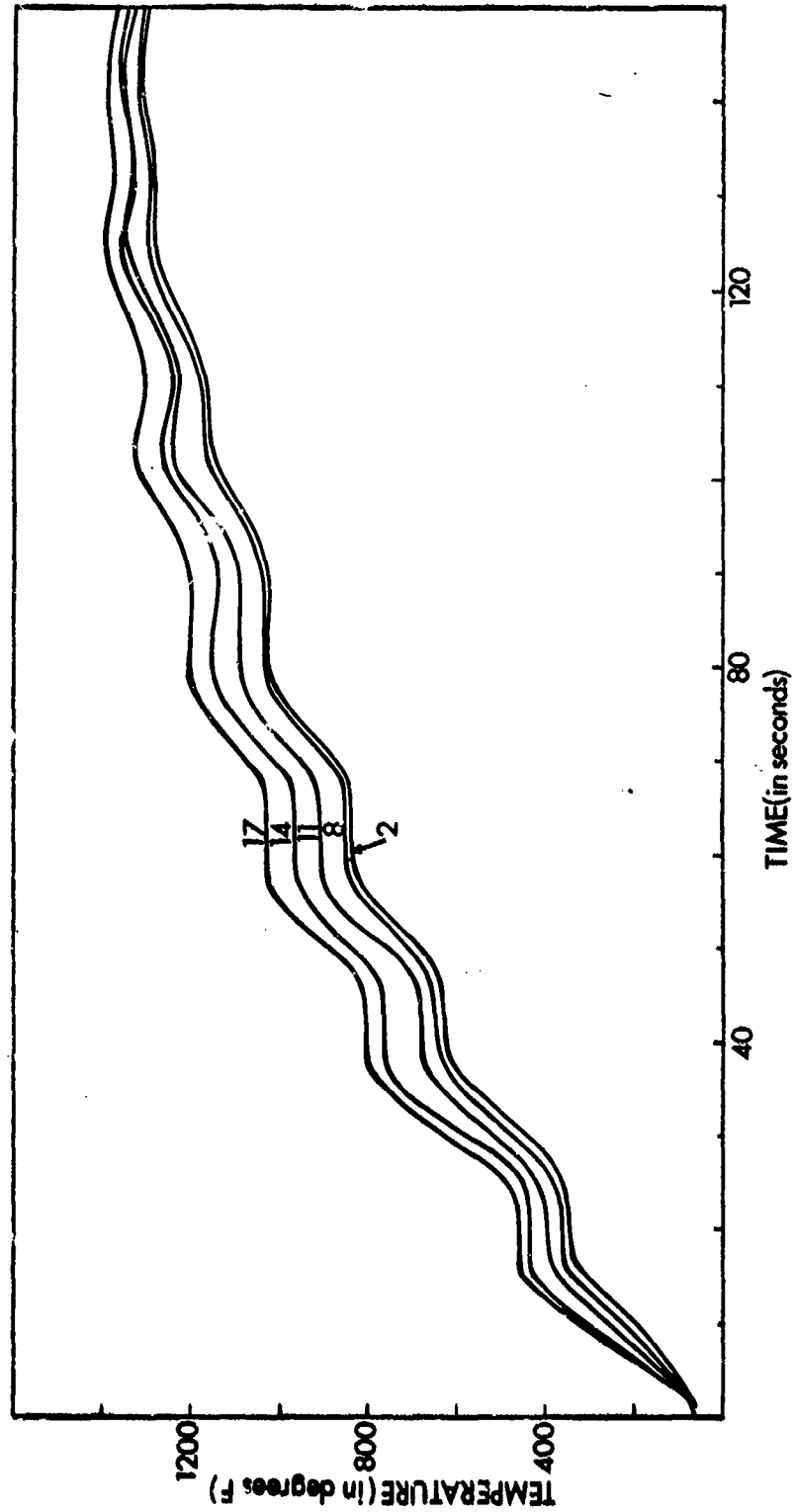in Cr-Mo-V Steel.   1000X

FIGURE 10   Recorded Temperatures of the Outside Surface
of an M60 Barrel During Firing.
The Numbers on the Lines Refer to the Distances
of Locations from the Origin of Rifling.

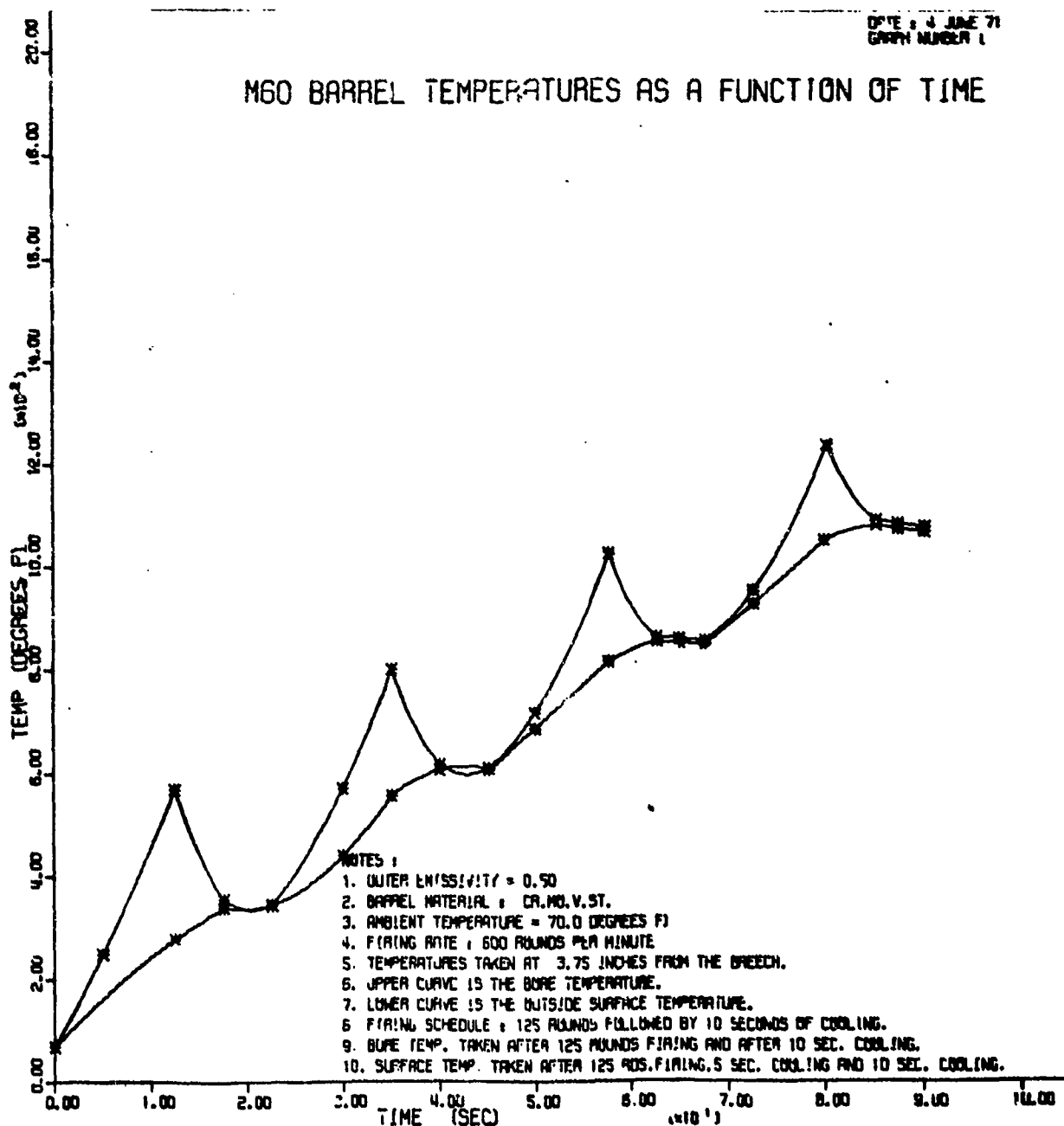17

FIGURE 11   Calculated Values of Bore Surface
              Temperatures and Measured Values of
       Outside Surface Temperatures of an M60 Barrel

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Some explanation is necessary about the phrase "cal-culated bore surface temperature." The temperatures at various radial locations after four bursts of 125 rounds with an intermediate cooling for 10 seconds are shown in Figure 12. Curves like this were generated for several points along the firing schedule. The implicit finite-difference method is applicable to regions very close to the bore surface. A small region still exists where accurate calculations are possible only if the nature of the slope can be defined. The bore surface temperatures quoted in this report do not refer to the "skin" of ma-terial at the bore surface. Also, each time a shot is fired, the bore surface temperature reaches a peak and quickly drops to a stable value. Attempts have been made in this laboratory to measure this temperature by carefully designed thermocouples positioned at the bore surface. A record of the measurements is shown in Figure 13. These peak temperatures are probably of value to study the chem-ical and the metallurgical reactions occurring in the bore; but, for mechanics considerations, only the lower end of the envelope is relevant because of the very short decay times.

The following general comments are given with respect to heat transfer characteristics in the barrel: The tem-perature gradient across the barrel section becomes in-significant at the end of each cooling interval (Figures 12 and 14). The fact that the outside surface gradually becomes heated as the firing continues and thus the tem-perature gradient is gradually decreased is considered important because of the following reasoning: The thermal stresses and the pressure stresses operate in opposite directions. When the outside surface is cold, the thermal stresses partially nullify the pressure stresses. But, when the outside surface is hot, the nullifying effect is decreased. Furthermore, this action occurs at a time when the barrel is mechanically weak. During service, the barrel is heated and cooled between the ambient temperature and temperatures as high as 1400°F. From this observation, the importance of the study of thermal fatigue in gun bar-rels is evident.

CALCULATED RADIAL TEMPERATURES FOR THE M60 BARREL

NOTES:
7. OUTER EMISSIVITY=0.50
2. BARREL MATERIAL: CM.MO.V.ST.
1. AMBIENT TEMPERATURE=70.0 DEGREES F.
5. FIRING RATE: 600 ROUNDS PER MINUTE
4. TEMPERATURE AFTER 500 RDS.
3. TEMPERATURE TAKEN AT 3.75 INCHES FROM THE BREECH
6. FIRING SCHEDULE: 125 ROUNDS FOLLOWED BY 10 SECONDS OF COOLING

FIGURE 12   Calculated Values of
Radial Temperatures. The Radial
Distances are Measured from the Axis of the Barrel Tube

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Typical Record of Bore Surface Temperature During First Seven Rounds

Bore Surface Temperature of First Round on
Extended-Time Scale in 7.62mm Gun

FIGURE 13

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CALCULATED RADIAL TEMPERATURES FOR THE M60 BARREL

NOTES:
7. OUTER EMISSIVITY=0.50
2. BARREL MATERIAL: CN NO.V.ST.
1. AMBIENT TEMPERATURE=70.0 DEGREES F.
5. FIRING RATE: 600 ROUNDS PER MINUTE
4. TEMPERATURE AFTER 500 RDS. AND 10 SEC. COOLING
3. TEMPERATURE TAKEN AT 1.75 INCHES FROM THE BREECH
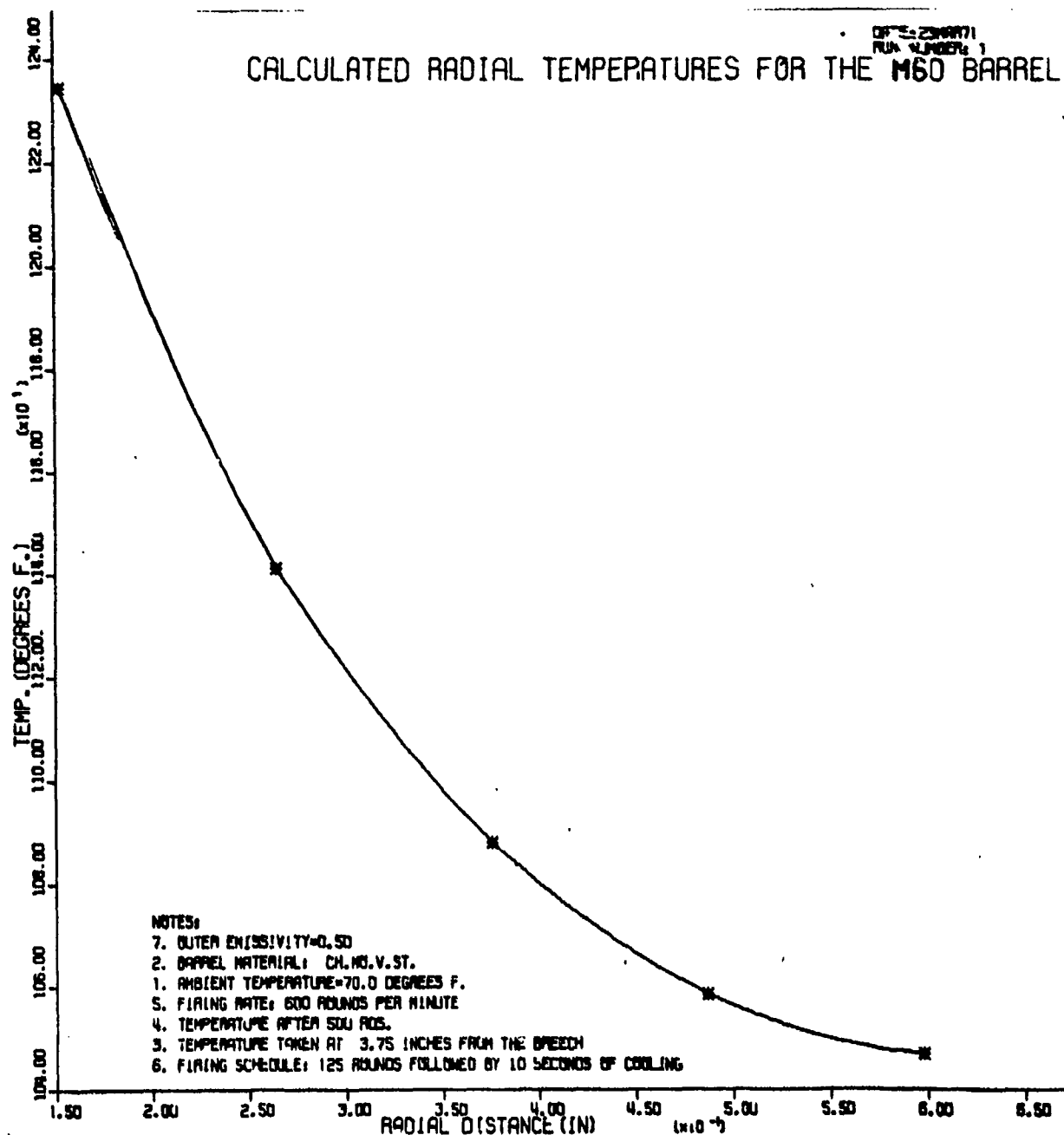6. FIRING SCHEDULE: 125 ROUNDS FOLLOWED BY 10 SECONDS OF COOLING

FIGURE 14   Calculated Values of
          Radial Temperatures. The Radial
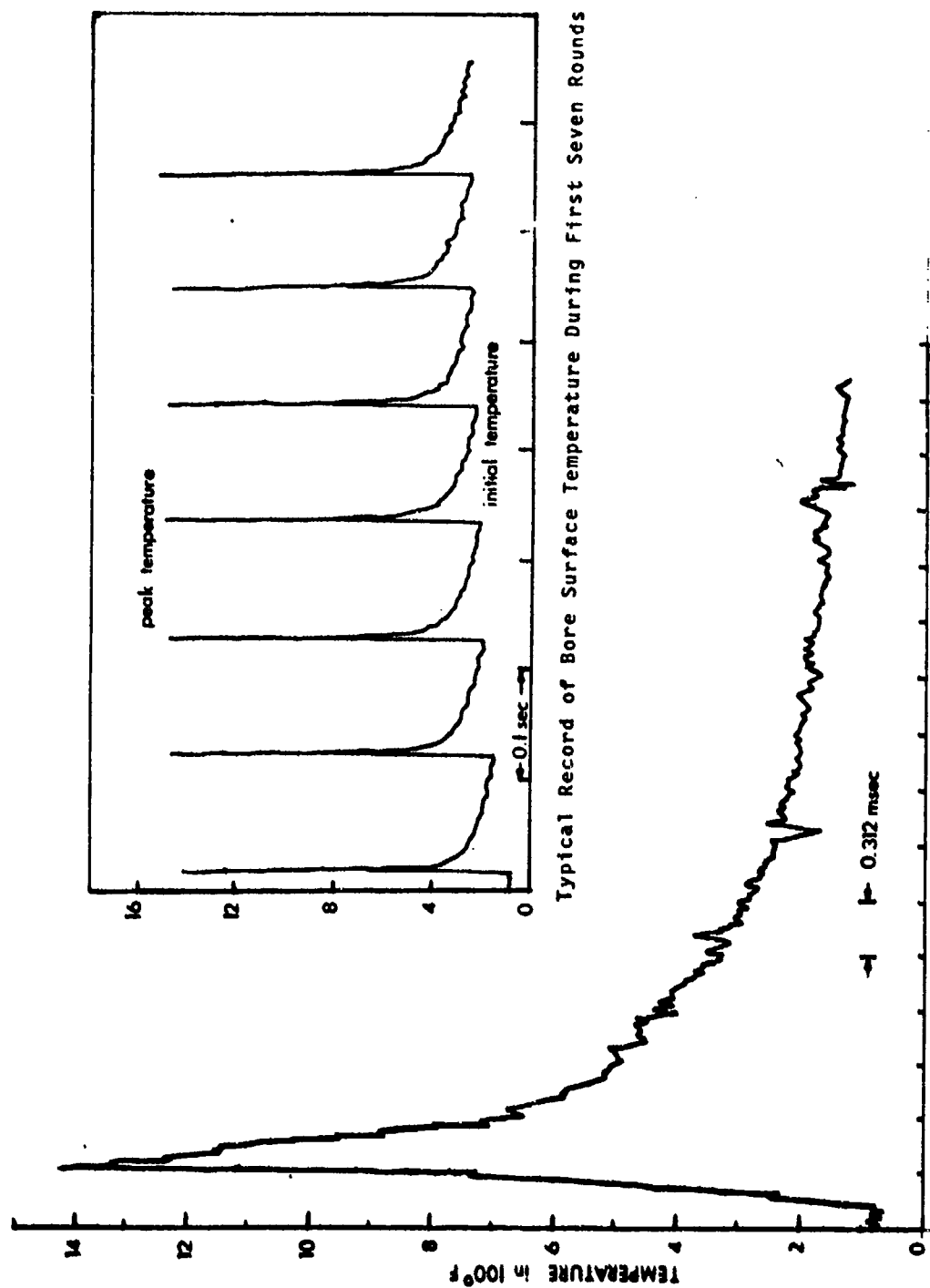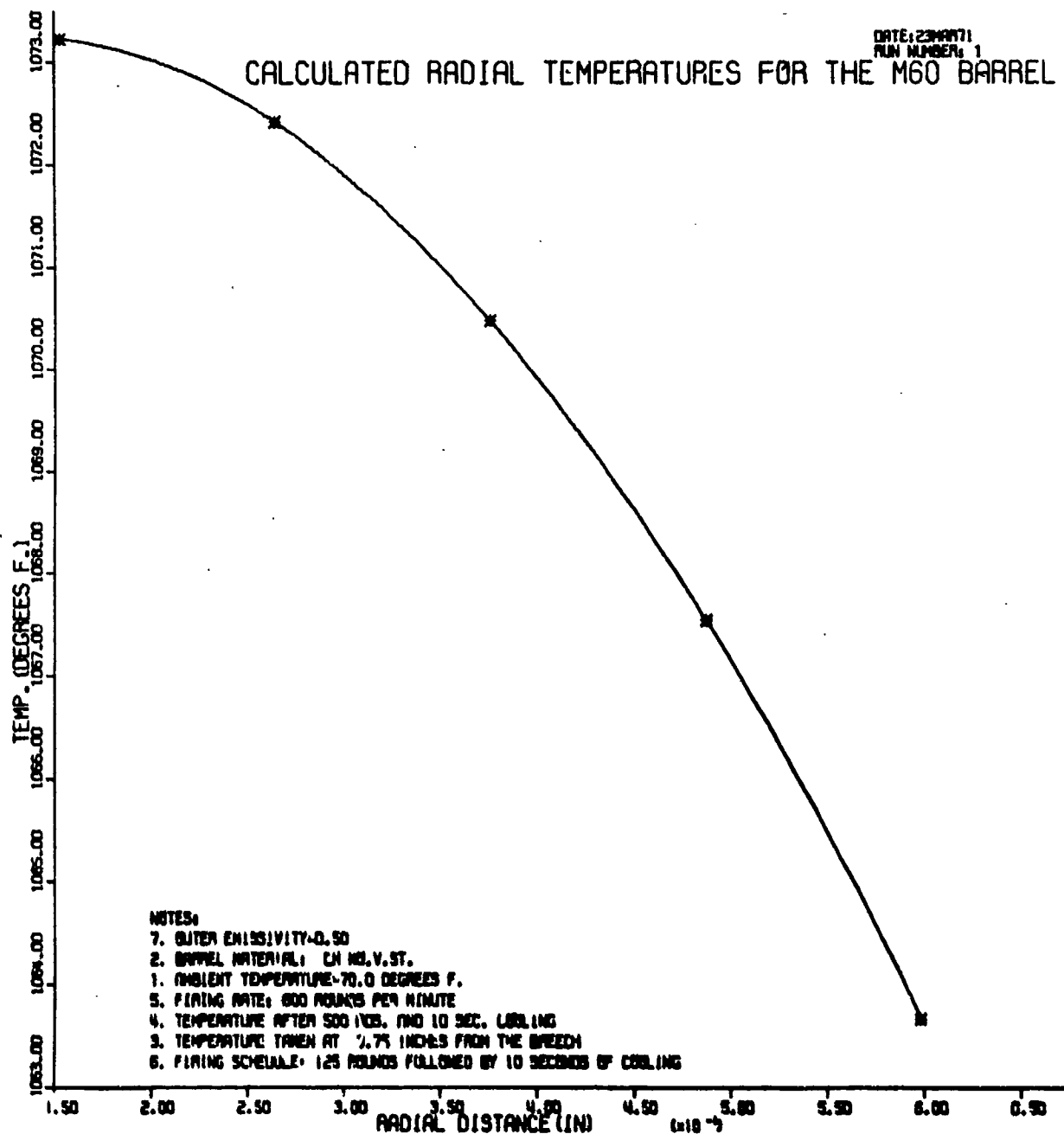Distances are Measured from the Axis of the Barrel Tube

CONCLUSIONS

1. The effect of static tensile stress is to lower the amplitude of the alternating stress corresponding to the endurance limit of Cr-Mo-V steel.

2. The method of "universal slopes" is applicable to the prediction of fatigue life of Cr-Mo-V steel.

3. The fatigue properties and the characteristics of fatigue fracture of Cr-Mo-V steel are similar to those of other quenched and tempered, fine-grained, low-alloy steels.

FUTURE WORK

Thermal stresses in the 7.62mm barrel during firing will be calculated as a function of time from the data obtained during the first year. The coupling of these data with pressure stresses will result in a stress-time profile representative of gun barrel service. Three different kinds of fatigue testing are planned for the future. They are: (1) thermal fatigue studies based on the temperature data, (2) fatigue tests under programmed-loading and constant temperatures up to 1500°F, and (3) fatigue testing under programmed temperatures and constant stress amplitude. The investigation will be carried out toward the understanding of the phenomenon of fatigue in gun-barrel materials.

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